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Abstract
Effective decision-making requires information, but how much information is enough and how much money should be invested in additional information is often unclear. This paper attempts to assess the economic benefits of informational investments, specifically of investments in Earth Observation (EO) for managing the Great Barrier Reef. We develop an expert elicitation approach based on Bayesian Decision Theory to estimate the expected contribution of informational investments to decision-making. We hypothesize that EO can improve decision-making by allowing for better-targeted emission reduction measures in the Great Barrier Reef (GBR) lagoon. For assessing the benefits (cost savings) of improved targeting we develop a model to optimize emission reductions under different states: emissions from all catchments may affect reef quality, or emissions from certain catchments may affect reef quality more. The states reflect the current uncertainties relating to water quality management in the region. The analysis suggests that the expected benefits of EO information for managing the GBR can be substantial, and depend on the perceived accuracy of EO information and on decision-makers prior beliefs.

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1. Introduction

In its report on the role of global Earth Observation (EO) for coral reef protection, the Integrated Global Observing Strategy (2003) argues that further investments in EO information are required to improve coral reef protection worldwide. The Strategy makes no attempt, however, to determine the amount of additional investments needed or to quantify the benefits associated with better-protected reefs. Evaluating costs and benefits is important for determining optimal investment levels and convince policy-makers that investments are indeed required. Few studies have, however, quantitatively assessed the economic benefits of EO information or, for that matter, evaluated the economic value of information for environmental management at all.

A short review of the literature suggests that the value of information literature is limited, and that few empirical estimates of the benefits of information exist. Traditionally, value-of-information studies focused on the value of weather information for agricultural production and management (Nordhaus and Popp 1997). Recently, the scope of studies has broadened by addressing the value of information on a broad range of stochastic events such as the El Niño-southern oscillation, the oil price disasters, forest fires, geomagnetic storms, and the internet (see Macauley, 2006, for an overview). A number of studies assessed the value of information in the field of environmental resource management, for example Gjerde *et al.* 1999 and Nordhaus and Popp 1997 in the area of global warming, and Borisova *et al.* 2005 in the area of water quality management. The value of EO for environmental resource management was assessed by Kaiser and Pulsipher 2004, Chiabai and Nunes 2006, and Isik *et al.* 2005, among others. Most of these studies compare decision-making under uncertainty with decision-making under perfect information, interpreting the difference as the value of information. This basically assumes that decision-makers use all information available and that information is perfect.

In this paper we argue that Bayesian decision theory is a more appropriate analytical framework. In Bayesian decision theory the value of information is determined by the extent to which decision-makers actually use the information to update their beliefs. This depends on the content and availability of the information, the perceived accuracy of the information and the prior belief decision makers have (Hirshleifer and Riley 1979). We examine the suitability of Bayesian decision theory in the case of EO investment for improved water quality monitoring in the Great Barrier Reef (GBR) lagoon, in order to better support management of the coral reef.

We are not the first to apply Bayesian decision theory for assessing the value of information. Bayesian decision theory is, for example, also used in the medical and health risk literature to estimate the value of information, but due to inherent difficulties in modeling the complexities of decision-making processes, it's use has been limited (Yokota and Thompson 2004). In this paper, we reduce the complexity of decision-making by assuming discrete probabilities instead of continuous probability functions, and by focusing the analysis on only two possible actions and two possible states of the world. Also, due to the inherent difficulties in measuring decision-makers' prior belief functions (Rabin 1998), few empirical applications of Bayesian decision theory exist. Lybbert *et al.* (2006) assess whether African pastoralists use weather forecasts to update their beliefs and Schimmelpfennig and Norton (2003) apply Bayesian decision theory to assess whether policy makers use the outcomes of economic research to change their decision-making. Both studies assess impacts *ex post*, asking decision-makers to express their expectation before and after receiving the additional information (Lybbert *et al.* 2006) or asking them to directly express how certain information changed their beliefs (Schimmelpfennig and Norton 2003). In this study, we assess the value of information *ex ante,* since it is the expected value of information that determines whether informational investments are made. Given that decision-makers are usually unaware of their prior belief function, asking them *ex ante* how information might change their decision-making is unlikely to generate trustworthy results (Rabin 1998). Hence, we focus our analysis on assessing decision-makers' perceptions of informational accuracy, which is the other factor determining whether decision-makers are likely to update their beliefs. We illustrated our approach previously in Bouma *et al.* (2009), but in this study decision-makers prior beliefs were clear: Bouma *et al.* (2009) assess the value of EO for preventing potential harmful algal blooms in the North Sea, using the probability of potentially harmful algal blooms as indicating the prior belief of decision-makers, also because this was the probability to which all respondents referred. This is very different in the case of water quality management in the Great Barrier Reef lagoon. Here, the added value of EO information lies not in early warning, but in better targeting of emission reduction investments. Prior beliefs regarding the spatial variability of pollution impacts are not well established, and neither are they shared. Under these conditions, applying Bayesian Decision Theory is more difficult, and prior beliefs have to be deducted from actual decision-making, in line with Lybbert *et al.* (2006).

The structure of the paper is as follows. In section 2 we introduce the case study. Section 3 presents the conceptual framework and in section 4 we elaborate the water pollution abatement cost model we developed to estimate abatement costs. Section 5 describes our empirical approach for the elicitation of decision-makers' perceptions and in section 6 we present the results. Section 7 discusses the outcomes of the assessment and concludes.

2. The case study

The GBR is the largest coral reef system on earth, stretching 2000 km along the coast of Queensland, Australia, and covering 348,000 km^2. Part of the GBR is designated a protected marine park and the entire reef has been declared a World Heritage site to recognize it's exceptional diversity and ecological value. Twenty-six major river basins, comprising 25% of the land area of Queensland, discharge into the GBR lagoon, climatically ranging from the wet tropics to semi-arid dry zones. Land use differs between the catchments, agriculture (i.e. sugar cane and horticulture) being the predominant form of land use in the wet tropics and grazing being the predominant form of land use in the semi-arid zones. Both agriculture and grazing are affecting water quality in the GBR lagoon, nutrient loads having increased 10-20 times since European settlement (Wooldridge *et al.* 2006). Besides nutrients, sediment and pesticide are causing damage to the reef (Brodie *et al.* 2008a, 2008b) and in 2001 a major plan, the Great Barrier Reef Water Quality Action Plan, was developed to improve the quality of water flowing from adjacent catchments into the lagoon.

The Great Barrier Reef Water Quality Action Plan is based on historical increases in sediment, nutrient and pesticide loads: Catchments with stark increases in sediment and nutrient run-off have higher reduction targets than other catchments (GBRMPA 2001). Emission reduction targets range from 33 to 50% and interventions are voluntary and mostly targeted at reducing sediment and nutrient emissions from the

cane and horticulture sector and from grazing. Since in the Northern region of the GBR catchment agricultural development is still limited, interventions focus mainly on the 21 catchments located in the middle (wet) and southern (dry) part of the GBR catchment. Our analysis will therefore concentrate on these catchments too.
Table 1 presents an overview of catchment characteristics and of the emission reduction targets set per catchment in the Great Barrier Reef Water Quality Action Plan.

Table 1 Characterization of catchments with targets of GBR water quality action plan.

River basin	Type	Total area	Sugar cane	Grazing	Sediment emissions	Nutrient emissions	TSS target	DIN target
		km2	km2	km2	TSS (ton)	DIN (ton)	%	%
Baffle creek	Dry	3996	14	3495	103376	874	50	33
Burdekin	Dry	130126	193	128640	2443232	11134	50	33
Burnett	Dry	33248	231	27944	728607	1244	50	33
Calliope	dry	2236	0	2032	60772	235	50	33
Fitzroy	dry	142537	0	124732	2635482	6579	50	33
Kolan	dry	2901	161	2349	61589	444	50	33
Styx	dry	3012	0	2961	136000	642	50	33
Boyne	dry	2590	0	2226	16974	314	33	33
Prosperine	wet	2535	196	2070	227314	1169	50	50
Plane creek	wet	2539	549	1830	114860	1612	50	50
Pioneer	wet	1570	296	1166	288343	471	50	50
O'Conell	wet	2387	264	1904	366309	1666	50	50
Johnstone	wet	2325	394	493	305142	1849	50	50
Tully	wet	1683	247	316	88084	1303	33	50
Rusell-Mulgrave	wet	1983	232	55	222425	1441	33	50
Murray	wet	1107	58	520	17098	440	33	50
Mossman	wet	466	57	15	15131	231	33	50
Herbert	wet	9843	691	7330	664787	1588	33	50
Haughton	wet	4044	528	3441	172454	801	33	50
Don	wet	3695	47	3582	509528	812	33	33
Barron	wet	2902	76	227	45877	321	33	33

DIN : Dissolved inorganic nitrogen, TSS: Total suspended sediment. Source: GBRMPA (2001).

Targeting investments to catchments, and regions within catchments, that most affect reef quality would probably be more efficient, but uncertainties regarding the linkages between land use, water quality and reef quality are large (Wooldridge *et al.* 2006, Brodie *et al.* 2008a, b). EO could reduce this uncertainty by increasing insight into the spatial and temporal distribution of certain water quality indicators in the GBR lagoon. Currently, ecological and water quality information concerning the GBR is scarce: Although in-situ measurements of certain parameters are available, due to its sheer size coverage for the entire reef is low (Prange *et al.* 2007). More EO information about water quality would make it possible to better target emission reduction measures to the catchments that most affect reef's quality, which could help reef protection and reduce water management costs.
Basically, there are four informational services that EO delivers to support water quality management in the GBR lagoon: a) Land use and land cover monitoring, b) sediment discharge and river plume monitoring, c) chlorophyll-a monitoring and d)

seagrass monitoring. The contribution of land cover and land use information is to help target sediment and nutrient emission reduction measures *within* catchments: Land cover and land use are important determinants of erosion rates and better information about land cover improves model predictions of sediment and nutrient flows (Kinsey-Henderson *et al.* 2007). River plume and chlorophyll-a information helps to improve targeting *between* catchments, as better information about the flow of sediments and chlorophyll-a from catchments makes it possible to determine which catchments are likely to most affect the reef (Haynes *et al.* 2007, Steven *et al.* 2007). Information about seagrass coverage helps targeting of measures *between* catchments, as it gives an indication of which parts of the reef most require protection from poor water quality. In this paper we focus on the contribution of EO sediment and chlorophyll-a information, since we are interested in *between* catchments targeting and since EO sea grass applications are still in an experimental stage.

Indications of what better targeting of water quality interventions in the GBR catchment may imply can be found in the scientific literature. With respect to sediment reduction, McKergow *et al.* (2005) argue that most of the sediment comes from two catchments, the Fitzroy and the Burdekin basin, and that targeting interventions to these regions is most effective for improving water quality in the GBR lagoon. With regard to nutrient emissions, the emerging consensus seems to be that nutrient emission measures are most effective in the wet tropical regions of the GBR catchment. Devlin and Brodie (2005), Wooldridge *et al.* (2006) and Fabricius (2005) show that the inner southern reefs of the Whitsunday group and the Wet tropics are most affected by high nutrient levels, and targeting nutrient reduction measures to the wet tropical regions seems most effective for avoiding further coral reef loss. Greiner *et al.* (2005) combine the different insights into an ecological impact indicator which uses information about relative catchment loads, river flow and flood regimes together with information about reef circumference and ecosystem health. We will use the Greiner *et al.* indicator as a proxy for the more targeted water quality management approach.
Estimates of the full costs of reaching the Great Barrier Reefs Water Quality Action Plan's targets are not available. For individual GBR catchments, studies of the costs of pollution abatement are available (see for example Roebeling *et al.* 2009, Rolfe *et al.* 2009, Van Grieken *et al.* 2008), which indicate that the costs of reaching the targets are substantial and that the costs of pollution abatement are much higher in the grazing sector, than in horticulture and cane (Roebeling *et al.* 2009, Rolfe *et al.* 2009). In the cane sector, for example, emission reductions of 20% are possible without any additional costs. Better targeting of measures between sectors and catchments can generate substantial cost savings, but decision-makers are uncertain about possible adverse effects. Investment in EO could help reduce this uncertainty. In the remainder of this paper we analyse under which conditions additional investments in EO make sense.

3. Conceptual Framework

Bayesian decision theory is concerned with decision-making under uncertainty. When decision-making is uncertain, decision-makers have to act upon their beliefs regarding the possible states-of-the-world. The states-of-the-world may be something like "it rains" or "it is dry" and decision-makers attach a certain probability "π_s" to each expected state of the world ($\Sigma\pi=1$). The role of information is that it gives a message "*m*" about the state of the world. Based on the informational message the decision-maker can "update" her beliefs about the state-of-the-world and, perhaps, change her decision ("take an umbrella"), or not. The value of information, then, depends on the extent to which the decision-maker updates her beliefs and the impact this has on the expected utility of decision-making. A formal way of expressing the process of belief updating is reflected in the well-known Bayes' theorem:

$$\pi_{s,m} = \Pr(s \mid m) = \frac{\Pr(m \mid s)\Pr(s)}{\Pr(m)} = \frac{q_{m,s}\pi_s}{q_m} \tag{1}$$

with $\pi_{s,m}$ the posterior probability, or the updated belief, π_s the prior probability, or the belief before the additional information, $q_{m,s}$ the conditional probability of receiving message m given state s, and q_m the unconditional probability of receiving informational message m. The unconditional probability of receiving message m is related to the conditional probabilities (of receiving message m in state s) by:

$$q_m = \sum_{s=1}^{S} q_{m,s}\pi_s \tag{2}$$

Hence, whether an informational message succeeds in making a decision-maker change her belief depends upon the decision-maker's prior belief regarding the possible state-of-the-world and the perceived accuracy of the informational message. The 'value' of message m is simply the difference between the utility of the action that is chosen given message m (x_m) and the action that would have been chosen without additional information (x_0):

$$\Delta_m = u(x_m, \pi_{s,m}) - u(x_o, \pi_{s,m}) \tag{3}$$

The states referred to reflect the situation that decision-makers are uncertain about. In the case of water quality management in the GBR lagoon, for example, there is uncertainty as to which catchments should be targeted to optimally protect the coral reef. If the state-of-the-world is that emissions from all catchments affect the condition of the reef, the optimal policy is to invest in water quality improvement in all catchments discharging into the GBR lagoon. However, if the actual state-of-the-world is that only emissions from certain catchments affect the reef's condition, the optimal policy is to target these catchments first. Since we do not know in advance which message the information service will produce, the expected value of the information is the expected difference in utilities of actions given the likelihoods of receiving messages m (q_m):

$$\Delta(\mu) = E(\Delta_m) = \sum_m q_m \left[u(x_m, \pi_{s,m}) - u(x_o, \pi_{s,m})\right] \tag{4}$$

$\Delta(\mu)$ is the expected utility of the new information, and can thus be used as an indicator of the value of this information, or the decision-maker's maximum willingness to pay.

Applying Bayesian decision theory to the case of water quality management in the GBR lagoon first requires defining the alternative actions and possible states-of-the-world. Although a whole range of alternative actions would be possible, we simplify the decision-making problem to two alternative actions and two possible states-of-the-world. With regard to the potential actions we define action x1) as reducing pollution from all catchments proportionally (non-targeting) , and action x2) as reducing pollution from some catchments proportionally more than from others (targeting). With regard to the 'states-of nature' we assume s1) there is no spatial variability in the impacts of pollution, and s2) there is spatial variability in the impacts of pollution. The simplified decision-making problem is illustrated in table 2.

Table 2 Pay-off matrix of the decision-making problem.

	Actions (x)	
States (s)	x1: Non-targeting	x2: Targeting
S1: No spatial variability in impacts	Payoff (x1|S1)	Payoff (x2|S1)
S2: Spatial variability in impacts	Payoff (x1|S2)	Payoff (x2|S2)

In principle, pay-offs should reflect the net benefits of interventions, i.e., the benefits in terms of the economic value of better reef quality minus the costs of pollution abatement. Estimating these benefits is difficult, however, because of a number of reasons relating to uncertainty on dose-effect relationships and uncertainty with respect to the marginal valuation of the reef. Hence, we take a somewhat simplifying, cost-effectiveness approach assuming that the environmental effectiveness of actions is fixed, but that better informed decision-making can reduce water quality management costs. In the next sections we further explain our approach.

4. Water pollution abatement costs

We estimated water pollution abatement costs with a cost-minimization model that was developed for this study, written in the programming language GAMS. Given an exogenous environmental target, the model computes the least-cost abatement policy across catchments and crops. In the model we distinguish between 2 pollutants, 21 catchments and 2 crops. The two pollutants are dissolved inorganic nitrogen (DIN) and total suspended sediment (TSS); the two crops are sugar cane and other crops (mainly grazing). The objective function of the model is:

$$AC = \min_a \sum_p \sum_r \sum_i f_{pri}\left(a_{pri}\right) \tag{5}$$

AC= Total abatement cost
$f(a)$ = Abatement cost for pollutant p from crop i in catchment r as function of abatement intensity a.

The abatement cost is minimized given a constraint on the effectiveness of the abatement policy on the protection of the Reef. The effectiveness is the product of the total pollution flowing into the GBR lagoon and an "ecological impact" indicator that determines the relative damage of pollutants from different catchments. We use one constraint for each pollutant. In formula:

$$\bar{A}_p = \sum_r v_{pr} \sum_i P_{pri} * a_{pri} \tag{6}$$

$\bar{A}_p$ = Total abatement target for pollutant p = {DIN, TSS}
v_{pr} = Ecological impact indicator of pollutant p from catchment r
P_{pri} = Current pollution levels of pollutant p from catchment r and crop i.

Data on current pollution levels of DIN and TSS per catchment were taken from the Great Barrier Reef Marine Park Authority (GBRMPA 2001). For the allocation of pollution across sugar cane and other crops we estimated pollution coefficients (tonnes per km^2) for sugar cane from the work of Roebeling *et al.* (2009) for the wet tropics, and van Grieken (2008) for the dry tropics. Pollution from other crops was estimated by subtracting pollution from sugar cane production from total pollution loads per catchment as presented in GBRMPA (2001).

We estimated quadratic abatement cost functions for DIN and TSS from sugar cane and grazing from the results of Roebeling *et al.* (2009). Because the cost data in Roebeling *et al.* relate to one catchment in the wet tropics (the Tully-Murray catchment), we compared the cost data with data from other studies from other catchments (Rolfe *et al.* 2009; Donaghy *et al.* 2007, Lu *et al.* 2004), both from the wet and dry tropics. The analysis did not suggest major differences in abatement cost functions between different catchments. Therefore we applied the Roebeling *et al.* abatement cost functions to all catchments. In accordance to Roebeling *et al.*, in our model we set a maximum percentage of 80% to DIN abatement and a maximum of 60% to TSS abatement per crop and per catchment.

To distinguish between the states of the world, we assume that in the first state pollution loads discharged by the different catchments fully affect the reef (impact factor 1). In the second state, we assume that pollution loads from some catchments affect reef quality more (impact factor >1) and from other catchments affect reef quality less (<1). We use the ecological impact factors of Greiner *et al.* (2005) as a proxy for the second state of the world. To reach the same amount of total emission reduction, we rescale the impact factors.[1] Table 3 presents the ecological impact factors per catchment and per pollutant.

Table 3 Ecological impact factors per catchment.

	Greiner *et al.* (2005)	Re-scaled: impact TSS*	Re-scaled: impact DIN*
Baffle creek	0.59	0.43	0.46
Burdekin	1.69	1.24	1.31
Burnett	1.24	0.91	0.96
Calliope	0.7	0.51	0.54
Fitzroy	1.51	1.10	1.17
Kolan	0.37	0.27	0.29
Styx	0.66	0.48	0.51
Boyne	0.5	0.37	0.39
Prosperine	1.03	0.75	0.80
Plane creek	1.37	1.00	1.06
Pioneer	1.07	0.78	0.83
O'Conell	1.14	0.83	0.88
Johnstone	1.41	1.03	1.09
Tully	1.13	0.83	0.88
Rusell-mulgrave	1.03	0.75	0.80
Murray	0.79	0.58	0.61
Mossman	0.56	0.41	0.43
Herbert	0.96	0.71	0.75
Haughton	0.79	0.58	0.61
Don	0.72	0.53	0.56
Barron	0.49	0.36	0.38

Re-scaled (per pollutant) with scale factor α such that $\sum 1 \cdot R_i = \sum \alpha \cdot GIF_i \cdot R_i$, where R_i is reduction target for catchment i in the GBRMPA and GIF_i is Greiner's Impact Factor for catchment i.

[1] Rescaling procedure is explained underneath Table 3.

We carried out four simulations. The first simulation is a cost-effective abatement policy under the assumption of equal ecological damage from the pollution from all catchments (i.e. ecological impact factor for all catchments is equal to 1). At the overall and catchment level this simulation resembles the abatement policy plan of GBRMPA, the Great Barrier Reef Water Quality Action Plan, although there are (minor) differences in abatement rates for individual catchments. The second simulation is a cost-effective simulation under the assumption of different ecological damages from the pollution from different catchments, using the re-scaled ecological impact factors presented in table 3. Hence, abatement levels are higher in those catchments that are believed to cause more harm to the Reef. We will call this policy approach “targeting” (i.e. abatement effort is targeted to those catchments that cause most damage). In the third and fourth simulations, the policies from the first and second simulations are carried out, but now the ‘perceived’ ecological impact factors differ from the ‘real’ ones. Hence, in the third simulation, the first (no-targeting) policy is implemented, while in fact damage from a unit of pollution differs from catchment to catchment. In this case, the intensity of abatement may have to be adjusted to meet the overall pollution targets. In the fourth simulation, a targeting approach is followed, while in fact there is no difference in damage from pollution from different catchments. Table 4 presents the total costs of abatement per simulation.

Table 4 Total abatement cost of the four simulations (million AUD/year).

	X1	X2
S1	1471	1521
S2	1531	1392

Of the four options, abatement cost is lowest with a policy of targeting when in fact there is spatial variability in impacts (X2|S2: AUSD 1,392 million per year). Abatement cost of this policy is much higher however when there is no spatial variability (X2|S1: AUSD 1,521 million per year). With a non-targeting policy, abatement cost is lowest with no spatial variability (X1|S1: AUSD 1,471 million per year) and highest with spatial variability (X1|S2: AUSD 1,531 million per year). Which policy would be best depends on the probabilities of the states, to which we will now turn.

5. Prior beliefs and the perceived accuracy of information

To estimate the extent to which information is used to update decision-makers’ beliefs, we need to know the prior beliefs and the perceived “accuracy” of the message, i.e. the conditional probability of message *m* given state *s*. (equation 2) Most decision-makers are not well aware of their current belief system, and have difficulties expressing their beliefs regarding the different states-of-the-world. Prior belief functions can, however, to some extent also be deducted from past decisions. We will return to this issue later. First, we concentrate our efforts on assessing the perceived accuracy of the information, or the conditional probability of message *m* given state *s*. Basically, what we are trying to assess here are, in statistical terms, the type-I and type-II errors associated with informational message ‘*m*’. A type-I error occurs when an informational message incorrectly rejects the ‘true’ state and a type-II error occurs if the informational message fails to reject the ‘false’ state. This is something decision-makers can make an estimate of, as the results of Schimmelpfennig and Norton (2003) and Bouma *et al.* (2009) show.

To elicit decision-makers' perceptions of the accuracy of EO information, we developed a questionnaire in close cooperation with CSIRO Land & Water, the University Queensland and the Queensland Environmental Protection Agency. To assess the perceived type-I errors we asked respondents to give an indication of the present (without EO) and expected future (with EO) 'informedness' of decision-making, 'informedness' referring to the certainty with which decisions are being made. The type-I error of EO information was then determined as the remaining uncertainty, or 1- the expected 'informedness' of decision-making with access to EO. To determine the type-II errors, we inquired about the perceived accuracy of EO information, or the probability that EO indicates, for example, a certain type of land cover (or sediment level, chlorophyll-a level or seagrass cover) when this is in reality not the case.

Prior to the questions, we informed respondents about the potential informational EO services, presenting respondents with EO images regarding land cover, river plumes, chlorophyll-a concentrations and seagrass cover and a short, explanatory text. Also, we asked some questions about the respondent's background, about their beliefs and expectations with regard to EO and about the importance of water quality management. Finally, we asked respondents to state their confidence in their answers and evaluate the questionnaire. We sent the questionnaire to approximately 70 researchers, water managers and policy-makers concerned with the management of the GBR. Respondents were selected by CSIRO on the basis of their position (e.g. role in water quality management) and exposure to EO. Explicit attention was paid to respondent representation from research and policy circles and direct or indirect involvement in the management of the GBR. We sent the questionnaire around mid May 2008, and respondents had till mid July to respond. By the time the deadline closed, 27 respondents had replied, or approximately 40%.

Of these 27 respondents, 42% were policy-makers and water managers directly involved in GBR-, water quality- and/or catchment-management, 31% were researchers and 27% of the respondents described themselves as somewhere in between. With regard to the respondents' background in environmental monitoring and use of EO information, 92% of the respondents indicated having considerable experience with environmental monitoring. With respect to EO, all respondents indicate having had some exposure, but only 31% had had considerable experience with EO, 38% of the respondents some and 31% of the respondents little experience (of which 4% none).

All respondents gave estimates of what they perceived to be the informedness of decision-making, and most respondents were confident about the estimates they gave. Researchers, and those with most EO experience, were more confident than managers and people with little EO experience, but even the least confident were quite confident about the answers they gave. Hence, even for a complex environmental decision-making problem like the one addressed in this study decision-makers seemed able to express what they believe to be the accuracy of information.

Table 5 Results of the questionnaire.*

	Overall	Land cover	River plume	Water Quality**	Sea grass
Present 'informedness'[a] of decision-making	44 % (17.3)	41% (15.5)	42% (16.8)	45% (18.3)	49% (18.1)
Future 'informedness'[b] of decision-making	72% (13.5)	73% (12.8)	72% (16.7)	72% (11.9)	72% (12.6)
Impact of EO on 'informedness' of decision-making	28% (16.7)	32% (14.7)	30% (18.7)	27% (15.2)	23% (17.4)
Accuracy of EO[c]	65% (16.2)	65% (16.9)	67% (18.3)	66% (16.6)	62% (13.1)

[*] Standard deviations between brackets, ** chlorophyll-a

[a] We asked respondents: 'If 100% represents a situation of fully informed decision-making regarding X and 0% represents a situation with no information, what do you believe to be the 'informedness' of decision-making if decision-makers have NO access to satellite observation (thus would rely solely on in situ measurements)?

[b] We asked respondents: ' Now, with full access to satellite imagery derived X information, what do you believe the situation to be, i.e. how well-informed is decision-making then?'

[c] We asked respondents 'Given an image like X, what do you expect to be the probability that the satellite-based information indicates low water clarity when 'in situ' measurements indicate water clarity is good? (i.e. the accuracy of satellite-based river plume information)

Interpreting 1- the future informedness of decision-making as the type-I error of EO, the perceived type-I errors of having a monitoring system with additional EO investment are approximately 28%. For an indication of the perceived type-II error of an EO enhanced monitoring system we used the accuracy estimate itself. Due to unclear wording we encountered some difficulties in the interpretation of results. Some respondents gave estimates for the perceived accuracy of EO information (generally, in the range of 50-100%) whereas other respondents gave estimates for the probability of EO information being wrong (in the range of 0-50%). We corrected the second set of answers by subtracting all estimates below 50% from 100%, and checked outcomes with the maximum accuracy estimates respondents gave later in the questionnaire.
Testing for the influence of the respondent's background and level of EO experience, we find that when grouping respondents by professional background, there are no significant differences in 'informedness' estimates between groups. When we group respondents by their experience with EO information there are significant differences between groups (5% significance level, non-parametric Kruskal-Wallis test), but groups only differ in their estimates of the current 'informedness' of decision-making, and not in their estimates of the future 'informedness'of decision-making. Since it are the future 'informedness' estimates we are interested in, we can use the average figures for our analysis. Also, since the estimates for EO river plume and EO water quality information are roughly the same, we can use one estimate for both (i.e. a type-I error of 28% and a type-II error of 34%).

As a final step in estimating the value of EO for managing water quality in the GBR lagoon, we need to deduce decision-makers' beliefs regarding the current 'state-of-the-world'. As indicated earlier, decision-makers are unlikely to be able to express their prior beliefs regarding the different states-of-the-world, so we need to deduct these probabilities from actual decision-making. Assuming decision-makers are rational, the actions decision-makers take implicitly reflect their prior beliefs. With information about the expected utility of the alternative actions, this makes it possible to explicitly distinguish the prior beliefs. Given the fact that decision-makers are currently choosing action x1, the expected utility of action x should exceed the expected utility of action x2. Table 6 presents the expected utility of the different actions under the different states (NB expected utilities are negative because we are talking about costs).

Table 6. The expected utility of alternative actions under different states.

Prior belief S1 (%)	Prior belief S2 (%)	Expected utility x1 (million AUD)	Expected utility x2 (million AUD)
90	10	-1477	-1508
80	20	-1483	-1495
70	30	-1489	-1482
60	40	-1495	-1469
50	50	-1501	-1457
40	60	-1507	-1444
30	70	-1513	-1431
20	80	-1519	-1418
10	90	-1525	-1405
73.5	26.5	-1486.9	-1486.8

When the prior belief in state 1 is roughly 74%, the expected utilities of action x1 and x2 are the same. Hence, we assume that the prior belief in state 1 is minimally 74% when assessing the value of information.

6. Results

If we indeed assume a prior belief function for state s1 of 74%, and use the type I and type II errors presented in table 5, the value of EO information, $\Delta(\mu)$, can be calculated with the help of equation 4. Using the suggested parameter values, the value of EO information (in terms of cost savings) is 13.9 million AUD/year. It is important to note that this is a maximum estimate, given that when the expected utility of both actions is similar, decision-makers are most uncertain as to what action to choose. When decision-makers are more certain about their actions, the value of information is decreased. Figure 1 illustrates this relationship and presents the value of information for the whole range of prior beliefs. The figure also shows the value of information for the case when information is perfect, interpreting ‘perfect’ as the perceived maximum information accuracy, which respondents believed to be 80%. Finally, the figure presents the 95% certainty range of value of information estimates, accounting for the differences in respondent beliefs (based on standard deviations).

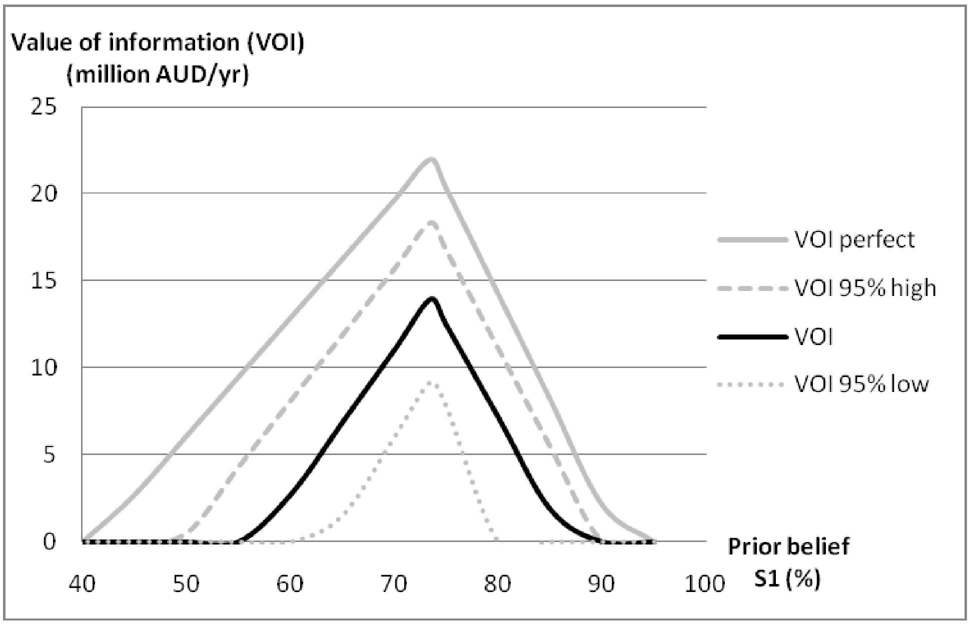

Figure 1. The value of EO information.

What the results presented in Figure 1 show, is that improving information accuracy not only increases its value, but also increases the range of prior beliefs over which the information has value. Whereas the least accurate information (represented by VOI 95% low) has only value to decision-makers with a prior belief in state 1 of somewhere between 60-80%, highly accurate information has a value for decision-makers ranging from strong state 1 believers to those that think state 2 is more likely to represent the actual state of the world. Attaching a single value to the contribution of EO information is difficult, since the value of information depends on what the decision-maker believes. Still, the figures give a good indication of the range of dollar amounts decision-makers might be willing-to-pay for EO information and on what this value depends.

What is still lacking from the figures are EO investment costs. Although data on the costs of EO investment are, unfortunately, lacking, studies have shown that the additional monitoring costs of EO are often negative (cost saving) or low: Bouma *et al.* (2009) indicate that EO reduces the costs of monitoring and Mumby *et al.* (1999) suggest that in the GBR region EO is most cost-effective too. Still, at low values of information, the additional costs may be too high, but for a range of values it seems worthwhile to invest in an activity that might well generate over 10 million AUD a year.

7. Discussion

We started out this paper with the aim of examining whether Bayesian decision theory could be used to assess the value of information for a complex environmental decision-making problem, having illustrated in Bouma *et al.* (2009) that it can be used to estimate the value of information for a simple decision-making problem, i.e. relating to early warning systems for algal bloom in the North sea.

The analysis showed that the methodology is indeed suitable for assessing the value of information when decision-making is complex. In fact, it showed that even when the prior beliefs of decision-makers are uncertain, Bayesian decision theory can derive value of information estimates and generate a range of values reflecting potential willingness-to-pay for the informational service. What makes the approach

particularly interesting is that it actually quantifies how increasing the accuracy of information increases it's value and also increases the range of decision-makers (with different beliefs) that are potentially willing to pay for the informational service. Although it may not be possible to exactly determine whether decision-makers attach a probability to state 1 of 62% or 74%, the outcomes provide a platform to discuss the conditions under which informational investments make economic sense.
For future studies, we would like to also include the benefits of better targeting and the costs of EO investment: Clearly, we would have preferred to this in this study, but the data to do so unfortunately lacked. Also, we implicitly assumed that decision-makers are risk-neutral. It could well be the case that the decision-makers in this case are risk averse and it would be interesting to see how this would influence our results. Finally, given the differences in decision-makers perceptions, it would be interesting to further analyze the factors influencing respondent beliefs.

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